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OPTICAL FILTERING DEVICE USING A PROGRAMMABLE DIFFRACTIVE ELEMENT, AND CORRESPONDING SPATIAL SPECTRAL BAND ROUTER AND CHROMATIC DISPERSION COMPENSATION DEVICE

The domain of the invention is telecommunications by optical fibres. More precisely, the invention relates to a technique for making tuneable optical filters, used particularly for the design of spectral band routing devices and chromatic dispersion compensation devices.

Spectral band routing and chromatic dispersion compensation functions are particularly important when using new generation optical communication networks.

Thus for example, routing of spectral bands is essential to share a source with multiple wavelengths between the hub office of a service provider and a content supplier, as described in the article by C.F. Lam et al. entitled "Programmable optical multicasting in a region: metro area network using a wavelength selective optical cross-connect", Proc. ECOC 01 Amsterdam, October 2001, pages 614-615.

Several techniques for routing spectral bands are known at the moment, particularly the technique proposed in the article by J.K. Rhee et al. entitled "Variable pass-band optical add-drop multiplexer using wavelength selective switch", Proc. ECOC 01 Amsterdam, October 2001, pages 550-551. This solution proposes to implant wavelength selective switches or insertion-extraction multiplexers with variable spectral bands, and is based on an optical configuration in free space using spatial liquid crystal modulators.

This solution can be used to make filters with a flat profile over a wide spectral band and continuous filtering between adjacent channels. The channels are firstly demultiplexed using a fixed diffractive lens, and then imaged on a spatial light modulator (SLM) that acts as a spatial wavelength filter. The width and selectivity of the channel are determined by the number of activated pixels or groups of pixels. The different channels are then recombined by inverse process.

The disadvantage of this solution is that two distinct optical elements have to be used, namely firstly a fixed diffractive optic performing a demultiplexing operation, then a spatial light modulator that performs a spatial filtering operation.

Therefore the routing device designed using this technique is not very compact. Furthermore, the use of several distinct optical elements tends to increase losses affecting the light signal and therefore to reduce the global efficiency of the routing device thus made.

Another disadvantage of this device is that it cannot precisely adjust the width and spectral selectivity of the different channels.

Like the routing function, chromatic dispersion compensation is a very important function in new generation optical communication networks, particularly when the transmission speeds envisaged are more than 10 Gbits/s, as described by V. Srikant in "Broadband dispersion and dispersion slope compensation in high bit rate and ultra haul system", OFC 2001, TuH1-1.

It should be noted that the chromatic dispersion problem is a result of the fact that each light pulse comprises several wavelengths, each of these wavelengths having different propagation characteristics in the medium considered.

Several techniques for compensation of chromatic dispersion are already known, some of which depend on the use of negative compensation fibres, while others depend on techniques based on excitation of high order propagation modes. Several techniques using chirped Bragg gratings and more recently solutions using a VIPA (registered trademark) type configuration in free space, are also known.

One disadvantage of these various chromatic dispersion compensation techniques that are applicable mainly to transport networks, is that they are not adaptive: in other words, they cannot be applied to spectral bands with variable chromatic dispersions.

Therefore, it is necessary to design an adaptive technique for the selection of variable spectral bands, both in the field of spectral band routing and compensation of chromatic dispersion.

One particular purpose of the invention is to satisfy this need and overcome the different disadvantages with techniques according to prior art.

More precisely, one purpose of the invention is to provide a technique for the selection of variable spectral bands and spectral band filtering with tuneable wavelength.

Another purpose of the invention is to provide such a technique that can advantageously be used for the design of spectral band routing devices and / or chromatic dispersion compensation devices.

Another purpose of the invention is to propose such a routing technique using a smaller number of optical elements than are used with techniques according to prior art.

Another purpose of the invention is to provide an adaptive chromatic dispersion compensation technique that can be applied to spectral bands with variable chromatic dispersions.

These objectives, and others that will become clear later, are achieved by means of an optical filtering device comprising at least one input optical fibre and at least one output optical fibre.

According to the invention, this type of device comprises means of transferring at least one spectral

band of at least one signal with multiple wavelengths incident through at least one of the said input optical fibres, to at least one of the said output optical fibres, the said means of transferring using at least one diffractive programmable element located in an intermediate plane between the said input optical fibre(s) and the said output optical fibre(s).

Thus, the invention proposes a quite new and inventive approach to selection and filtering of spectral bands. The invention is based particularly on the use of chromatic dependence characteristics of a programmable diffractive element. Therefore, it can advantageously be used to select an arbitrary spectral band centred on an arbitrary wavelength λ_i of an incident signal with multiple wavelengths, and transfer it to any output optical fibre in the filtering device thus formed, by appropriate programming of the programmable diffractive element.

Therefore, unlike techniques according to prior art, the invention can be used for adaptive selection of variable width and variable wavelength spectral bands, for the design of a spectral band filter with a tuneable wavelength. The filtering device according to the invention also has the advantage that it is more compact and simpler than known techniques according to prior art, since it only requires the use of one optical element, namely a programmable diffractive element. The use of such a device is particularly flexible and adaptable as a

function of characteristics of the incident signal and the filtering that is to be done.

Advantageously, such a device comprises programming means capable of modifying the spatial period of a pattern of the said programmable diffractive element, in at least one direction.

Preferably, the said programming means can be used to configure the said programmable diffractive element so that it has a spatial period *P* in the said at least one direction, such that a spectral band centred on a given wavelength λ_i is diffracted in the said at least one direction by the said programmable diffractive element at a predetermined angle θ_i such that $\sin\theta_i=\frac{k\lambda i}{P}$, where k is an integer number.

According to one advantageous characteristic of the invention, the said programming means introduce a disturbance to the said spatial period *P* equivalent to a variation less than the size of a pixel of the said programmable diffractive element.

Thus, an infinitesimal variation in the period of the grating can be obtained.

According to one advantageous embodiment of the invention, the said programming means can be used to configure the said programmable diffractive element such that it has a spatial period *P* comprising:

- at least one sub-period comprising N_1 pixels;
- at least one sub-period comprising N_2 pixels;

where N_1 and N_2 are two distinct integer numbers.

Preferably, such a device comprises a matrix with at least two output optical fibres each forming a spectral filter.

Advantageously, the position of the said output optical fibres in space is predetermined as a function of the filtering to be done.

Therefore, the arrangement of optical fibres within the output matrix is not arbitrary; it is preferably not regular. The output fibres thus form a physical filter for signals reflected by the programmable diffractive element.

Advantageously, the size of the core of the said output optical fibre is predetermined as a function of the filtering to be done.

The size of the core of the output fibres also controls the passband of the spectral filter that they make.

According to one advantageous characteristic of the invention, the said output optical fibres are located on at least one isochromatism circle.

According to a first advantageous variant of the invention, the said diffractive element is a programmable digital hologram.

Advantageously, the said programmable digital hologram is displayed on a spatial light modulator with amplitude or phase modulation levels, the said levels being continuous or quantified.

Preferably, the said spatial light modulator may be associated with at least one fixed diffractive element.

According to a first advantageous embodiment of the invention, such a device comprises a collimator lens, the said diffractive element acts in reflection and is located in the image focal plane of the said collimator lens, and the said at least one input optical fibre and one output optical fibre are located in an object focal plane of the said collimator lens, so as to form an optical set up in free space of the folded 4-f type.

According to a second advantageous embodiment of the invention, such a device comprises two collimator lenses, called the first and second lenses respectively, the said diffractive element is located in the image focal plane of the said first lens and in the object focal plane of the said second lens, the said at least one input optical fibre is located in the object focal plane of the said first lens, and the said at least one output optical fibre is located in the image focal plane of the said second lens, so as to form an optical set up in free space of the 4-f type.

Advantageously, such a device comprises a matrix of at least two output optical fibres, each of the said fibres being characterized by its position with respect to an optical axis of the said device, such that the said device forms a set of at least two tuneable filters, and it comprises holographic means for adjustment of the spectral selectivity of each of the said filters, as a function of the said position with respect to the optical axis of the said corresponding output optical fibre.

Advantageously, the said output optical fibres are single mode fibres.

According to one advantageous characteristic of the invention, at least one of the said single mode fibres has at least one lens at its end, so as to form a single mode fibre with lens.

Preferably, the said lens comprises at least one fibre segment with an index gradient added on by assembly and fracture.

Preferably, the said lens also comprises a silica fibre segment between the said single mode fibre and the said fibre segment with an index gradient added on by assembly and fracture.

Advantageously, such a device comprises means of adjusting a filter template applied to at least one of the said wavelengths.

Advantageously, the said filter template is superposed to the said programmable diffractive element.

Thus, a windowing function is superposed on the diffractive element. The action of such a windowing function is a spatial mismatch of the incident mode on the fibre, which affects the selectivity of this fibre in wavelength.

According to one advantageous variant, the said filter template is included in the said programmable diffractive element.

The corrective window then forms part of the digital hologram.

The invention also relates to a spectral band router comprising at least one optical device as described above, the said device(s) comprising at least two output optical fibres.

Preferably, in such a spectral band router according to the invention, the said diffractive element can be dynamically configured so as to route at least two distinct spectral bands of at least one incident signal, to corresponding distinct output optical fibres F_j.

Advantageously, the said programming means can be used to configure the said programmable diffractive element, such that the said programmable diffractive element has a spatial period P in the said at least one direction, corresponding to the combination of several spatial periods P_i, in which each of the said spatial periods P_i is such that when the said programmable diffractive element has the said spatial period P_i, a spectral band centred on λ_i is transferred to the said output optical fibre F_j.

Preferably, the said output optical fibres are located on an isochromatism circle, such that the said spectral bands are routed with constant passband.

The invention also relates to a chromatic dispersion compensation device, comprising an optical device like that described above.

Preferably, at least one of the said output optical fibres is connected to at least one fibre segment with negative chromatic compensation.

In a first advantageous embodiment of the invention, the said fibre segments with negative chromatic compensation have one reflecting end.

According to a first variant embodiment of the invention, the said output optical fibres are located on an isochromatism circle.

According to a second variant embodiment of the invention, the said output optical fibres are located on at least two distinct isochromatism circles.

In a second advantageous embodiment of the invention, one end of the said optical fibre segment with negative chromatic compensation is connected to a first output optical fibre, and the second end is connected to a second output optical fibre.

Preferably, the said first and the said second output optical fibres are diametrically opposite on an isochromatism circle.

Other characteristics and advantages of the invention will become clearer after reading the following description of a preferred embodiment, given as an illustrative and non-limitative example, and attached drawings among which:

- Figure 1 shows a block diagram of an optical filtering device according to the invention that may for example be applied to routing of spectral bands or compensation of chromatic dispersion;
- Figure 2 illustrates passband measurement results for the different filters in the device in Figure 1;

- Figure 3 illustrates two examples of patterns of the programmable diffractive element in the device in Figure 1;
- Figure 4 illustrates the coupling intensity in an output optical fibre of the device according to the invention, as a function of the wavelength, with the two examples of patterns in Figure 3;
- Figure 5 illustrates the passband of a filter in the device in Figure 1, as a function of the number of pixels per period of the programmable diffractive element;
- Figure 6 illustrates an example of positioning output optical fibres with respect to the optical axis of the device according to the invention;
- Figure 7 presents an example of routing of spectral bands starting from the optical filtering device according to the invention;
- Figures 8a and 8b illustrate the routing operation in Figure 7 in the form of result curves;
- Figures 9 and 10 illustrate a first variant embodiment of a chromatic compensation device according to the invention, comprising an optical filtering device in Figure 1, using negative compensation fibre segments with a reflecting end;
- Figure 11 presents a second variant embodiment of a chromatic compensation device according to the invention, comprising an optical filtering device in Figure 1, using negative compensation fibre

segments connected to two symmetric diffraction output fibres.

The general principle of the invention is based on the use of a periodic diffractive element (of the phase grating type) or a thin numeric hologram, used for deflection of an incident light beam and therefore advantageously makes use of chromatic dependence in order to make a tuneable filtering device. It is also based on the use of a matrix with output fibres that form a physical filter, through the size of their core and their positions in space.

An embodiment of an optical filtering device according to the invention is described in relation with Figure 1, capable of making an adaptive selection of spectral bands.

In one preferred embodiment of the invention, a double diffraction imagery set-up 1 (also called a 4-f set-up) is used comprising:

- a programmable digital hologram 2;
- an input optical fibre 3;
- a matrix 4 of output optical fibres;
- a collimator lens 5.

The programmable digital hologram 2 is located in the Fourier plane (2f), in other words in the focal plane of the collimator lens 5. The matrix 4 of output optical fibres is located in the focal plane of the collimator lens 5 symmetric to the digital hologram 2, as shown in figure 1.

The operating principle of the set up in Figure 1 consists of using the chromatic dependence of the periodic diffractive element 2 (that may for example be a phase grating or a thin digital hologram), when it is used for deflection of an incident beam by the input optical fibre 3.

In other words, we will consider the signal with multiple wavelengths 6, incident through the input optical fibre 3. This signal 6 comprises several distinct components with wavelengths equal to λ_i, where i varies from 1 to N. The device in Figure 1 can be used to select any spectral band from this signal 6, for example centred on a wavelength λ_2, and to transfer it to any one of the optical fibres in the output matrix 4. In the particular example in Figure 1, an attempt is made to transfer this spectral band to the output optical fibre reference 7.

One preferred embodiment of the invention is limited to the study of the first order diffractive properties of the hologram 2. However, higher orders (although with lower energy than the first order) may also be used since they have the advantage of providing greater angular dispersion. An output fibre in the matrix 4 is addressed by imposing the diffraction angle of the spectral band considered by the hologram 2.

The value of this diffraction angle is given as a function of the central wavelength of the spectral band considered and the spatial period of the hologram 2, by

the following gratings relation valid for a signal with normal incidence on diffractive element 2:

$$P\sin\theta = k\lambda \qquad (1)$$

λ, P, θ and k are the central wavelength of the selected spectral band, the spatial period of grating 2, the diffraction angle and order respectively. This formula is differentiated to derive the chromatic dependence of the diffractive grating 2 considered:

$$\frac{\delta\theta}{\delta\lambda} = \frac{k}{P\cos\theta} \qquad (2)$$

$\delta\lambda$ and $\delta\theta$ are the chromatic and angular dispersions respectively of the diffractive element 2. It should be noted that the angular dispersion $\delta\theta$ is greater for small spatial periods *d* of the grating 2 (in other words for high spatial frequencies of the diffractive element 2).

The output fibres in the matrix 4 form a plurality of spectral band filters as a function of their digital aperture.

These fibres 4 may be conventional single mode fibres and / or expanded core fibres. These aspects will be presented in greater detail in the remainder of this document.

The output fibres in the matrix 4 are characterized by their position with respect to the optical axis 8 of the device in Figure 1. The injection ratio of a signal in an optical fibre depends on the following relation:

$$T = \left(\frac{2w_r}{w_r^2}\right)^2 exp\left(\frac{-2\delta_r^2}{w_r^2+1}\right) \text{ where } \delta_r = \frac{\delta}{w_0} \qquad (3)$$

where w_r represents the width (or waist) of the incident beam,

w_0 represents the fibre mode width,

and δ represents the distance between the centre of the incident optical beam and the centre of the fibre core, also called misalignment.

Therefore the width of the passband of the different filters in the filtering device in Figure 1 will depend on the position of the corresponding output optical fibre of matrix 4, located at a variable distance from the optical axis 8 of the system, and the value of δ for a given wavelength. This dependence is illustrated by the experimental results in Figure 2, that show that as the distance between the output optical fibre considered and the optical axis of the system ("Out #14") increases, the passband in the corresponding filter becomes narrower.

The principle of the device in Figure 1 consists of making the wavelengths spectrum of the incident signal 6 move in front of the selected output optical fibre 7, to make filters with tuneable wavelength starting from output optical fibres in the matrix 4.

Considering the small size of the output fibre core 7 (typically of the order of 10 μm), the device 1 must enable sub-micronic displacements of the beam in front of the optical fibre 7, so as to precisely tune the passband of the corresponding filter.

These sub-micronic displacements are advantageously made possible in the device 1 by the use of a digital hologram or a thin diffractive grating 2. Under these

conditions, the deflection angle of the incident beam is determined by the resolution of the diffractive element 2, in other words by the size of the smallest element in the hologram or the grating 2 that can be independently adjusted. More precisely, if p is the size of a pixel in the diffractive element 2, and assuming a plane incident wave, the diffraction angles θ_i ($i = x, y$ in the direction of the abscissas and the ordinates) of this wave on the diffractive element 2 are given by equation (1) above expressed in the form:

$$\sin\theta_i = \frac{k\lambda}{pN_i} \qquad (4)$$

where N_i is the number of pixels used for each grating period in dimension i. In one preferred embodiment of the invention, the study is restricted to the first diffraction order in paraxial conditions (in other words in the case in which $k = 1$ and the values of the diffraction angle θ_i are low). Therefore, for θ_i close to zero, the previous expression (4) can be simplified to:

$$\theta_i = \frac{\lambda}{pN_i} \qquad (5)$$

A priori, the deflection angle θ_i can be modified by a variation of two adjustment parameters, namely the wavelength λ and the average number of pixels per spatial period N_i:

$$\delta\theta_i = \frac{1}{N_i p}\delta\lambda - \frac{\theta_i}{N_i}\delta N_i \qquad (6)$$

For a constant wavelength ($\delta\lambda=0$), a "digital" correction is made:

$$\delta\theta_i = \frac{\theta_i}{N_i}\delta N_i \qquad (5)$$

The smallest physical variation between two different gratings 2 corresponds to an additional pixel for each spatial period, namely $\delta N_i = 1$ in equation (5) above.

However, to enable a finer adjustment of the diffraction angle associated with a given wavelength λ, the inventors of this application considered using disturbances to the complete shape of the grating pattern, in order to obtain variations δN_i smaller than a pixel.

One example embodiment of such a disturbance is illustrated in Figure 3 that presents two almost identical patterns G_1 and G_2 of the grating 2 in a given direction.

The pattern G_1 of the diffractive element 2 is characterized by a number of pixels N_i per period in direction i, which produces a diffraction angle $\theta_i = \frac{\lambda}{N_i p}$ for a given wavelength λ. (Remember that p denotes the size of a pixel of the diffractive element 2).

The pattern G_2 of the diffractive element 2 is produced by the periodic sequence of sN_i+1 pixels in direction i, comprising s-1 sub-periods containing N_i pixels followed by a period containing N_i+1 pixels.

Therefore the average number of pixels per period for G_2 is equal to $\frac{N_i x(s-1)+(N_{i+1})}{s} = N_i + \frac{1}{s}$, which produces a diffraction angle $\theta_i^* = \frac{\lambda}{(N_i+\frac{1}{s})p}$ for a given wavelength λ.

Therefore, the corresponding angular difference between the two patterns G_1 and G_2 of the diffractive grating 2 is equal to:

$$\theta(G_1)-\theta(G_2) = \frac{\theta_i}{sN_i+1} \qquad (6)$$

The increase in the angular resolution of the device in Figure 1 induced by the passage from pattern G_1 to pattern G_2, compared with the value given by relation (5) where $\delta N_i = 1$, can be measured by the following ratio:

$$R = \frac{\delta\theta_i}{\theta(G_1)-\theta(G_2)} = s + \frac{1}{N_i} = s \qquad (7)$$

The smallest value of the oversampling factor s associated with a disturbance of the complete shape of pattern G_1 of the grating 2 is $s_{min}=2$. Therefore the value of s is also increased by the number N_{pix} of pixels in the thin programmable diffractive element 2 per dimension to $s_{max} = N_{pix}/2N_i$.

For the characteristic values of $N_{pix} = 1000$ and $N_i = 10$, the gain in angular resolution induced by the passage from pattern G_1 to pattern G_2, is R = 50.

Therefore with the process described above, the light beam can be moved infinitesimally in all directions in front of the fibre 7, simply by configuring the

pattern of the programmable diffractive element 2, for example by loading pseudo-periods corresponding to pattern G_2 into the programmable digital hologram 2. The output optical fibre 7 then becomes a band filter centred on a wavelength λ_2. This wavelength λ_2 is offset with respect to the corresponding central wavelength λ_1 previously obtained in the pattern G_1.

The wavelength offset of the passband of filter 7 induced by the passage from pattern G_1 to pattern G_2 is evaluated bearing in mind that the diffraction angle θ_1 must be kept constant during the passage from G_1 to G_2 (the addressed optical fibre remains the output fibre reference 7 during configuration of the hologram 2), which gives:

$$\lambda_2 - \lambda_1 = \frac{\lambda_1}{sN_i} \qquad (8)$$

The results in Figure 4 illustrate this offset in the wavelength induced by the passage from a pattern G_1 characterized by $N_i = 14$ to a pattern G_2 characterized by $s = 10$. Therefore, the result is an offset in the wavelength equal to $|\lambda_2 - \lambda_1| = 1548$ nm/140 = 11 nm for a spectral band filter 7 centred on a wavelength $\lambda_1 = 1548$ nm, before the hologram is reconfigured. Therefore after the hologram pattern has been reconfigured, the output optical fibre 7 forms a band filter centred on a wavelength $\lambda_2 = 1537$ nm.

If a single mode fibre module is used to design the matrix 4 of output optical fibres, the result is a bank

of tuneable filters. The spectral selectivity of each of these tuneable filters depends on the offset of the corresponding output optical fibre with respect to the optical axis of the system.

By making use of a chromatic dependence of the diffractive element 2 with respect to the positioning of the output optical fibres in the matrix 4 in the imagery plane, the spectral selectivity of each tuneable filter can be expressed as a function of the number of pixels per spatial period of the diffractive element 2. Since the mode imaged by the diffractive element 2 is centred in the imagery plane at a distance X_i from the optical axis, corresponding to the distance from the centre of the output optical fibre 7 to the optical axis of the device 1, we obtain:

$$\tan(\theta_i) = X_i/f \qquad (9)$$

In the paraxial condition $\tan(\theta_i) = \theta_i$, and for a given configuration of the diffractive element 2, $\delta N_i = 0$. Equation (9) can be differentiated to obtain:

$$\delta X_i = kf/(N_i p)\delta\lambda \qquad (10)$$

where p is the size of a pixel of the hologram 2.

If losses due to the offset in the wavelength are fixed to a value μ, for a given coupling value in dB, the result is:

$$\delta\lambda = \frac{0.96 N_i p w}{kf}\sqrt{-\mu} \qquad (11)$$

where w denotes the waist of the mode of the output optical fibre 7 considered.

Therefore, the passband of an output fibre is given by $\delta\lambda(\mu=-3\text{dB}) = 1.66 N_i p w / k f$. Therefore, it should be noted that as the pitch of grating 2 becomes smaller, the grating becomes more dispersive and the passband of the tuneable filter becomes narrower. The result for values of $p = 10^{-5}$ m, $w = 5 \times 10^{-6}$, $f = 40.5 \times 10^{-3}$ m and $N_i = 2$, is $\delta\lambda = 4.1$ nm. This value may easily be reduced by using higher orders (in other words for $k > 1$), but on the other hand the energy penalty will be higher.

The curve in Figure 5 illustrates the variation of the passband of a tuneable filter according to the invention as a function of the number of pixels per spatial period of the programmable diffractive element 2.

The size of the filter may be adjusted (in terms of uniformity and slope), by superposing a windowing function on the grating displayed on the programmable diffractive element. This type of method has been proposed particularly in the case of fixed elements by J. P. Laude and S. Louis in "A new Method for Broadening and Flattening the Spectral Shape of Transmission Channels of WDM Multiplexers and Routers", OECC'98, Techn. Digest, pp. 522-532, Chiba, Japan, July 1998.

The choice of output optical fibres in the matrix 4 is an important parameter in the design of the device 1 according to the invention. As described above, these optical fibres act as spectral filters, for which the width of the passband is a function particularly of the size of the fibre core.

In the matrix 4, the use of lensed single mode fibres of the type described in patent document FR 2 752 623 entitled "Method for manufacturing a collective optical coupling device and device obtained by such a method", also enables the production of a wide variety of filter banks using the technique according to the invention. For example, spectral filters with passbands between 100 nm and 2 nm can be constructed, while keeping low beam deflection angles on the diffractive element 2 (typically less than 3°), the value of which is limited mainly by the resolution of the programmable digital hologram 2 used.

Remember that these optical fibres are composed of conventional single mode fibres, at the end of which a fibre segment with an index gradient and possibly a silica fibre segment is added on by assembly and fracture, in order to make a single mode optical fibre with expanded core.

These optical fibres have the advantage that they enable mode diameters varying from less than 5 μm to several tens of microns, while maintaining the properties of a single mode fibre.

These output optical fibres may be arranged within the matrix 4, as shown in the diagram in Figure 6.

On this diagram, the matrix 4 comprises seven output optical fibres 12 distributed on two isochromatism circles reference 10 and 11 respectively. All optical fibres 12 located on the same isochromatism circle are located at the same distance from the optical axis 8 of

the system: therefore, they form tuneable filters with the same spectral band.

We will now describe an example of an application of the filtering technique described above with reference to Figures 1 to 6 for making a routing device, with reference to Figure 7.

According to one variant of the invention, the device 1 may be completed to add a routing function to the filtering function described above, to make spectral band selector-router filters. This variant embodiment advantageously uses the properties of digital holograms of being able to address several fibres simultaneously.

In the remainder of this description, an attempt will be made to describe a simple example embodiment, for simplification reasons, in which it is required to switch the spectral band between two output fibres in the device 1. Thus, in a first given configuration of the diffractive element 2, one fibre 71 forms a spectral band filter centred on a wavelength λ_1, and a second fibre 72 forms a spectral band filter centred on a wavelength λ_2. The objective is to configure the device 1, such that it routes the spectral band with wavelength λ_1 to the second output optical fibre reference 72, and the spectral band centred on λ_2 to the first fibre reference 71.

Obviously, the functions of the routing device are not limited to simple switching of two spectral bands, but include all routing operations that may be done given

an incident signal with multiple wavelengths λ_i and a plurality of output optical fibres.

Therefore the principle described below with reference to Figure 7 can be generalized to several fibres, subject to additional power losses induced by the holographic coding.

Consider the pattern R1 of the diffractive grating 2 which, according to the technique described above with reference to Figure 3, provides a means of switching a spectral band centred on the wavelength λ_1 to the fibre reference 71.

Consider also the pattern R2 of the diffractive grating 2, that switches a spectral band centred on the wavelength λ_2, where $\lambda_1 < \lambda_2$ to the fibre reference 72.

The programmable digital hologram 2 can then be configured so that it corresponds to the combination H of these two grating patterns R1 and R2, and therefore so that it routes the λ_1 band to the first fibre reference 71 and the λ_2 band to the second fibre reference 72. This combination corresponds to the addition of two grating reflection coefficients R1 and R2, $\hat{R} = \hat{R}1 + \hat{R}2$, accompanied by an appropriate holographic code C, operation symbolized by H = $C\hat{R}$. This operation is equivalent to a bridging operation, except that the spectral bands transmitted on each fibre are different.

When fibre references 71 and 72 are located on an isochromatism circle (for example the circle referenced

10 in Figure 6), the routing operation is then done with the constant passband.

In the future the objective is to switch these two spectral bands λ_1 and λ_2. This is done using the pattern disturbance method of grating 2 described above with reference to Figure 3.

In other words, the pattern R1 is modified slightly (using an associated pseudo-period R1') so as to move the spectrum towards the left (in other words in the direction of decreasing wavelengths), in the direction of the arrow referenced 7 in Figure 7. Thus, the wavelength of the incident spectral band is offset on fibre reference 71, so that it is now centred on λ_2. Similarly, the pattern R2 is modified slightly (using an associated pseudo-period R2') so as to move the spectrum towards the right (in other words in the direction of increasing wavelengths), in the direction of the arrow reference 74 in figure 7.

The hologram H' resulting from the composition of these two pseudo-periods R1' and R2' can then be formed, which gives the required result as illustrated in Figure 7: the spectral band centred on λ_2 is now transmitted to the optical fibre reference 71, and the spectral band centred on λ_1 is transmitted to the optical fibre reference 72. A wavelength routing operation is thus performed simply by changing the configuration of the programmable hologram 2 from H to H'.

As mentioned above, this operation can obviously be extended to the case of a plurality of output optical fibres.

Figures 8a and 8b present curves representing losses in output optical fibres 71 and 72 as a function of the wavelength, for hologram configurations H and H'. In figure 8a, the passband of the fibre reference 71 is centred on λ_1 = 1530 nm, and the passband of the fibre reference 72 is centred on λ_2 = 1550 nm approximately. After reconfiguring the hologram 2 according to the pattern H', the fibre reference 72 has a spectral band centred on λ_1 = 1530 nm, and the fibre reference 71 has a spectral band centred on λ_2 = 1550 nm, as illustrated in Figure 8b.

We will now present example applications of the tuneable spectral band filtering technique according to the invention to the production of a chromatic dispersion compensation device, with reference to Figures 9 to 11.

In this type of chromatic dispersion compensation device according to the invention, the output optical fibres in the matrix 4 of the filtering device 1, acting as spectral band filters, are connected to special negative chromatic compensation fibre segments. These fibre segments may have different characteristics in terms of slopes or spectral bands. The value of the chromatic compensation induced by this type of fibre segments is determined by their length, as described in the article by M. Hirano et al. entitled "Dispersion

compensating fibre over 140 nm bandwidth", ECOC October 2001.

The choice of the optical compensation fibre and its length are dependent on the required quality factor Q defined by the equation $Q = D/\alpha$ (11) where D is the dispersion (in ps/nm/km) and α is the attenuation (in dB/km and as a function of λ) of the signal transported by the compensation fibre.

Figures 9 and 10 illustrate a first variant embodiment of a chromatic dispersion compensation device in which the compensation fibre segments 20, 21 and 22 are used as mirrors.

The filtering device 1 according to the invention is designed according to a 4-f type set up, therefore the result is perfect imagery, in the plane, of the matrix 4 of output fibres (which corresponds to the waist plan, w_0) and the fibres can then be used as a mirror without loss of information.

For example, after a path through the dispersion compensation fibre 20 and reflection at the end 23 of this fibre, the signal is retro-propagated and follows the inverse optical path to recombine in the output fibre 24 with signals that followed other paths, in other words that used other dispersion compensation fibre segments 21 or 22.

This type of output fibre 24 corresponds to the input fibre reference 3 of the device in Figure 1.

The principle described above can be used to make an adaptive variable compensation. The device in Figure 9

has the advantage of automatically recombining signals after compensation in fibre segments 20 to 22, without it being necessary to use an additional recombination device.

In the variant embodiment in Figure 9, filters with the same spectral width are used by selecting output optical fibres 30, 31 and 32 located on the same isochromatic circle 11. In this device, the modulable parameters correspond to the choice of the spectral band, which is determined by the configuration of the hologram 2 used and the value of the compensation determined by the choice of an optical fibre 30, 31 or 32 in the output plane.

On the other hand, in the variant embodiment shown in Figure 10, work is done on two different spectral bands, by selecting two distinct isochromes references 10 and 11. Thus, the incident signal is transferred to two output optical fibres references 33 and 34, located on the isochromatism circles 10 and 11 respectively. Each of these fibres 33 and 34 is connected to a dispersion compensation fibre segment 37, 36, the end of which is covered by a reflecting treatment 23, so that these fibre segments 36, 37 act as a mirror. In the same way as for the set up in Figure 9, the signals are retro-propagated in fibres 33 and 34 and are then recombined in the fibre reference 24.

Figure 11 shows a third variant embodiment of the chromatic dispersion compensation device according to the invention, to avoid retro-propagation of the signal in

the output optical fibres in the matrix 4, and therefore the treatment at the end of dispersion compensation fibre segments.

According to this variant, a dispersion compensation fibre segment 42 is connected at each of its ends to two output optical fibres reference 40 and 41 located on the same isochromatism circle 11. These two optical fibres 40 and 41, diametrically opposite the isochromatism circle 11, correspond to two symmetric diffraction orders of the programmable digital hologram 2 of the device 1 according to the invention.

For example, this type of configuration corresponds to the case of a holographic system at binary phase level. The set up in Figure 11 requires that the two optical paths are balanced, firstly from the input fibre 24 to the output optical fibre 41, and secondly from the output optical fibre 40 to the input fibre 24 in the reverse direction. However, the error induced by an unbalance of these two optical paths remains low compared with the chromatic dispersion compensation provided by the fibre reference 42.